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Fermi Acceleration in jets

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Extragalactic Relativistic Jets:
Cause and Effect
ICTS - TIFR Campus, Bangalore, India
12-20 October 2015

All that we want is………

We seek a theoretical framework for understanding the origin of non-thermal particle distributions in plasma conditions relevant to extra-galactic jets

A complete theory should account for competing processes:

- unscreened E fields
- shocks
- turbulence
- magnetic reconnection
- large-scale shear, expansion
- cooling
- time/spatial dependence along jet
- …………

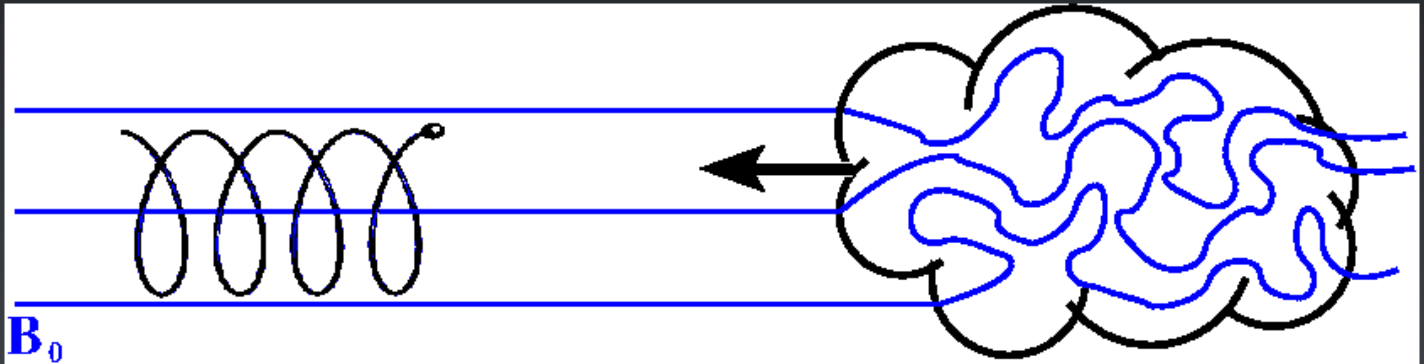
Through matching with observations, can we infer additional information about plasma conditions, jet launching / confinement / propogation ?

Fermi Acceleration

Fermi Acceleration

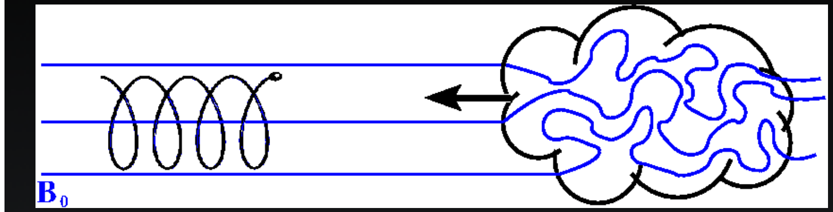
Ideal MHD “the norm” in astrophysical plasmas: $\boldsymbol{E} = -\boldsymbol{V}_{\text{flow}} \times \boldsymbol{B}$
Electric field vanishes in the local fluid frame!

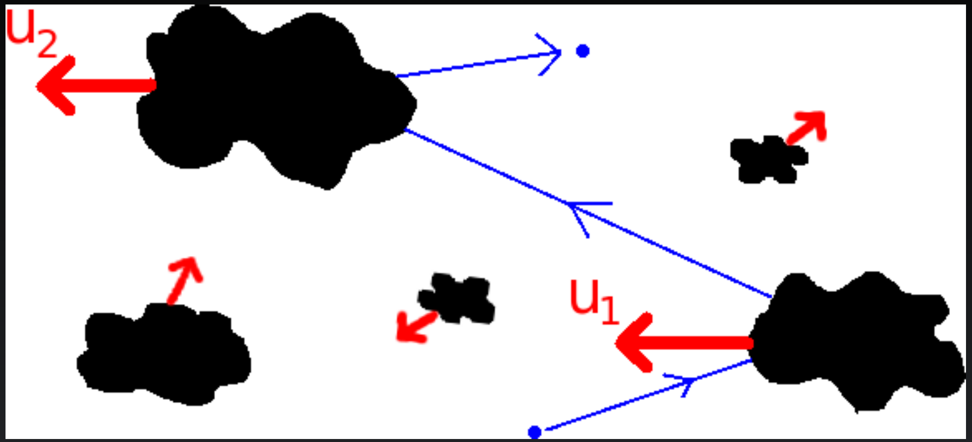
- Look for sites where ideal MHD approx. breaks down
  (Unscreened electric fields near blackholes, reconnection sites)
- Look for locations with flow velocity gradients



Fast particles collide with moving magnetised clouds (Fermi 1949). Particles can gain/lose energy depending on whether the collision is head-on/overtaking. Head-on collisions slightly more probable

Fermi Acceleration





Can (in theory) accelerate particles to high energy, although is said to be "slow"

$$\left\langle \frac{\delta E}{E} \right\rangle \sim \left(\frac{V_{\rm flow}}{v} \right)^2 \qquad t_{\rm acc}^{-1} = \left\langle \frac{1}{E}\frac{dE}{dt} \right\rangle \sim \left(\frac{V_{\rm flow}}{v} \right)^2 \nu_{\rm sc}$$

Can (in theory) produce non-thermal particle spectra, but sensitive to balance of acceleration vs escape

$$\frac{dN}{dE} \propto E^{-(1+t_{\rm acc}/t_{\rm esc})}$$

Modern theories have replaced moving clouds by MHD waves/ turbulence, but the essential idea is the same.

Stochastic Acceleration in Lobes

Cen A lobes $t_{\rm lobe} > 10 \text{ Myr}$

e.g. Hardcastle et al 08

Larmor's formula: $\left\langle \frac{dE}{dt} \right\rangle = \frac{4}{3} c \sigma_T \gamma^2 U_{\rm tot}$

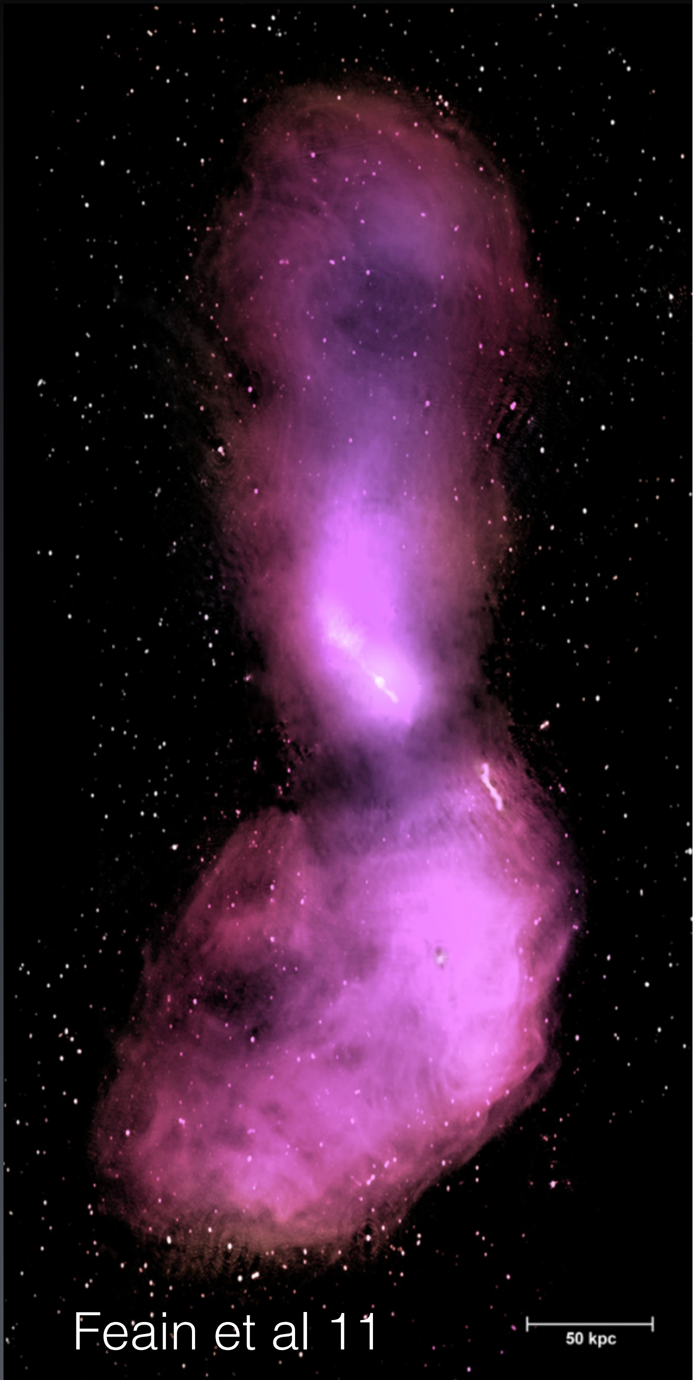
$$t_{\rm cool} \sim \left(\frac{E}{1 \text{ TeV}} \right)^{-1} \left(\frac{U_{\rm tot}}{0.5 \text{ eV cm}^{-3}} \right)^{-1} \text{Myr}$$

For Kolmogorov turbulent spectrum:

$$t_{\rm acc} \sim \left(\frac{n_{\rm p}}{10^{-4} \text{ cm}^{-3}} \right) \left(\frac{\lambda_{\rm max}}{10 \text{ kpc}} \right)^{\frac{2}{3}} \times \left(\frac{B}{1 \ \mu\text{G}} \right)^{-\frac{7}{3}} \left(\frac{E}{1 \text{ TeV}} \right)^{\frac{1}{3}} \text{Myr.}$$

Acceleration dominates cooling for E < 100GeV

O'Sullivan, BR & Taylor 09

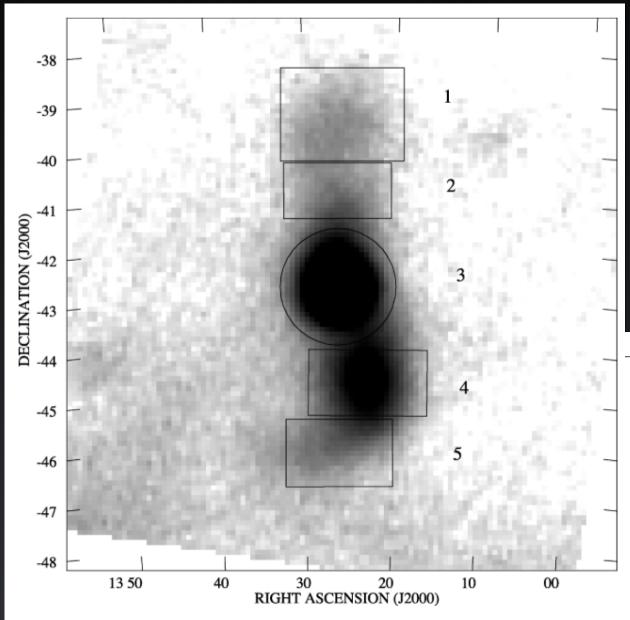


Feain et al 11

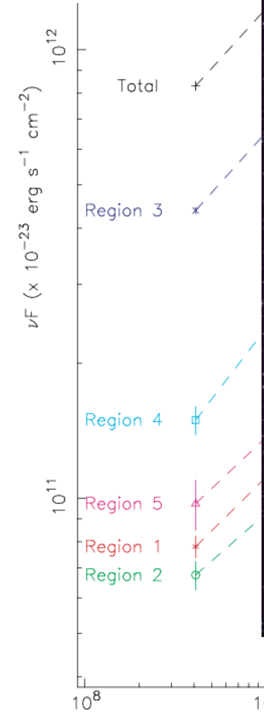
Stochastic Acceleration in Lobes

Can not ignore
stochastic acceleration

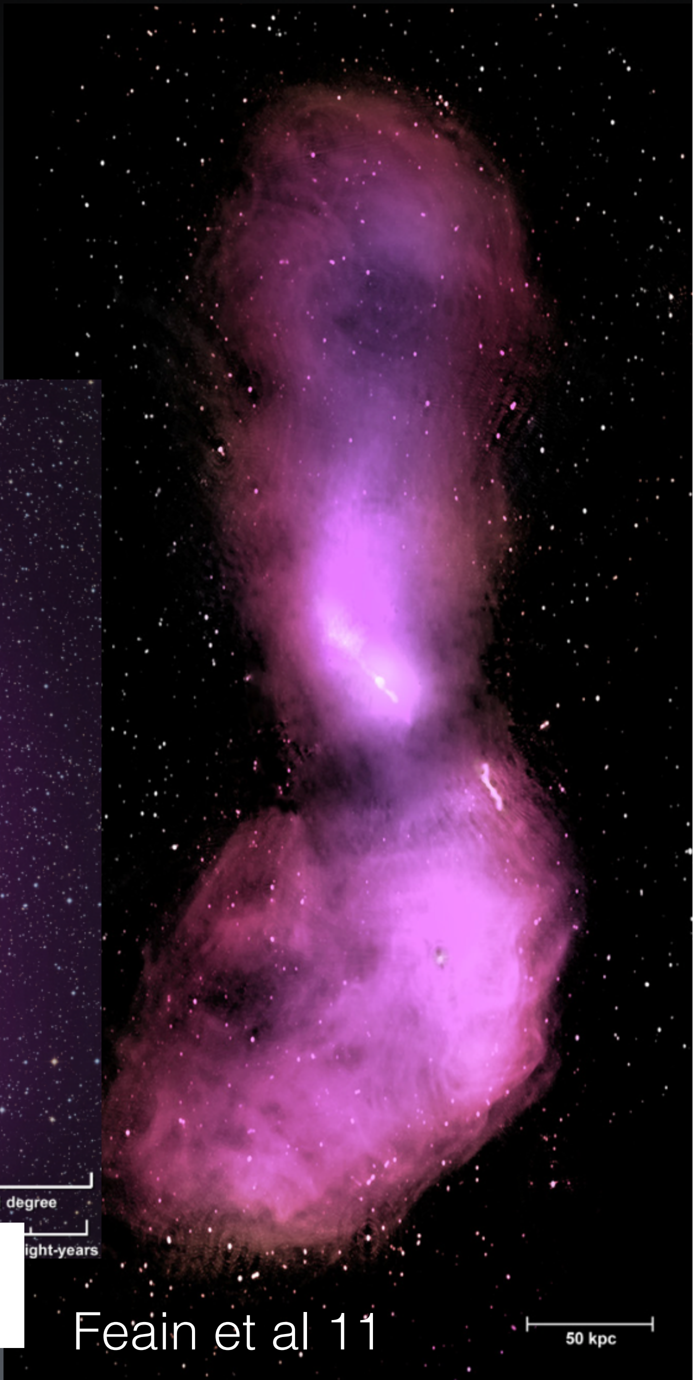
~ 100 GeV in $\sim \mu$G field



Hardcastle et al 08



Credit: NASA/DOE/Fermi LAT Collaboration, Capella Observatory



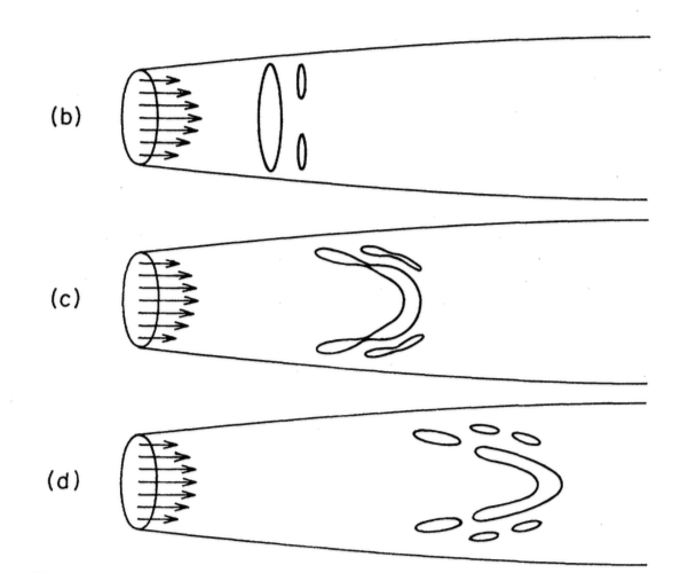
Feain et al 11

Fermi Acceleration in Shear Flows

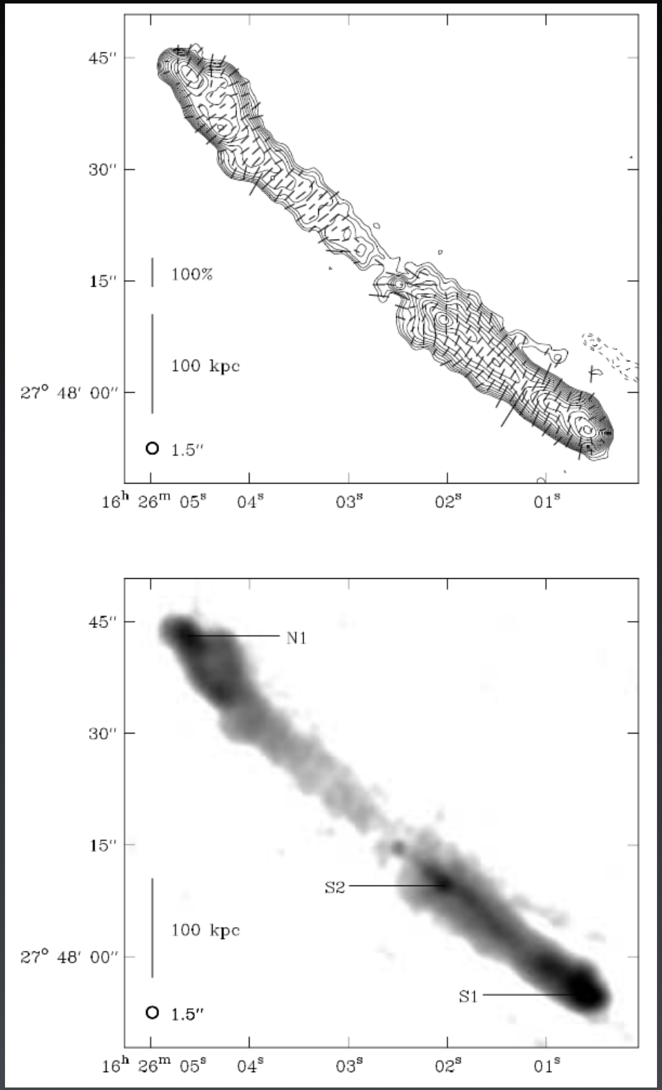
Shear Acceleration

Longitudinal apparent fields prevalent in powerful jets —

Evidence for strong shear?



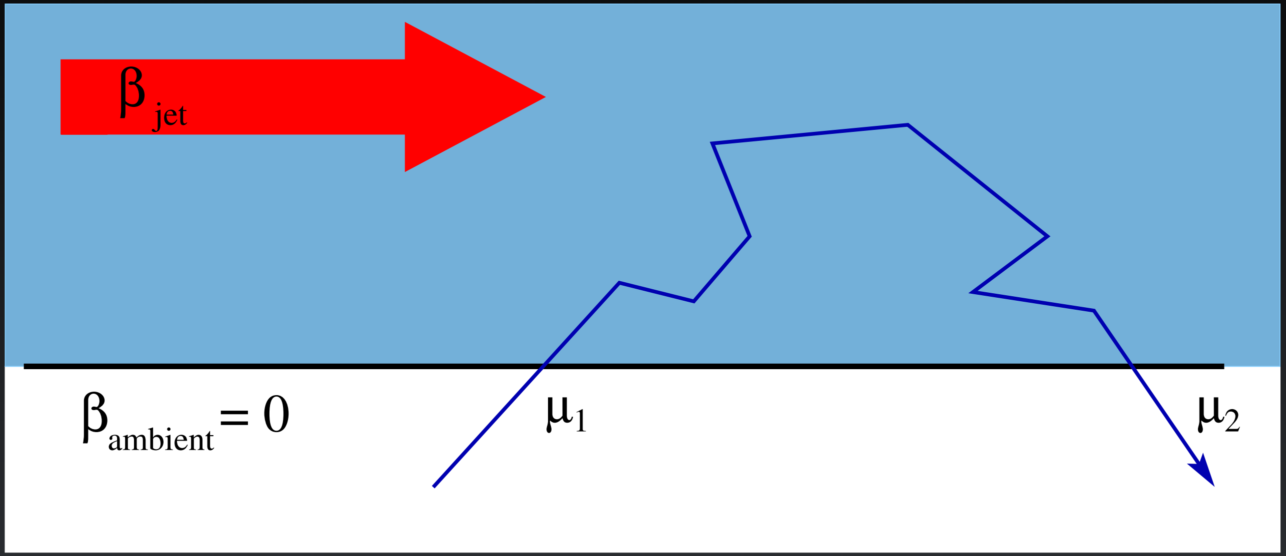
Begelman et al. 1984



Gilbert et al 2004

If flow profile retains information of launching, identification of specific signatures of shear acc. offers an indirect probe

Shear Acceleration



For simplicity consider discontinuous velocity profile

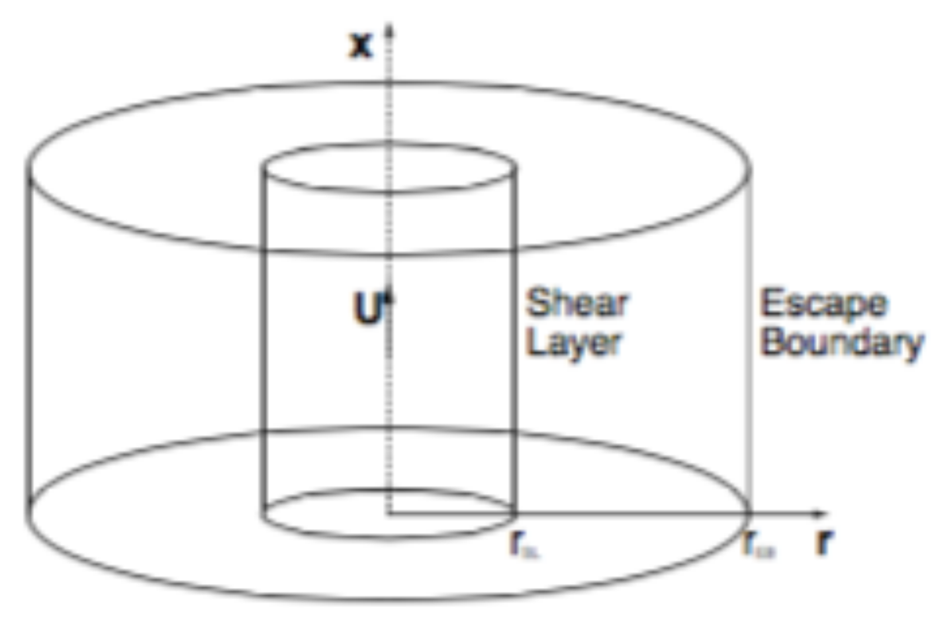
$$\frac{\Delta E}{E} = \beta_{\rm jet}\frac{\mu_2 - \mu_1}{1 - \beta_{\rm jet}\mu_2}$$

e.g. Ostrowski 90, Rieger & Duffy 04

No advection to balance diffusion,
we expect very flat spectra to be produced.
Will be sensitive to nature of particle transport —
knowledge of mean B-field crucial.

Shear Acceleration simulations

Test particle simulations in synthetic turbulence

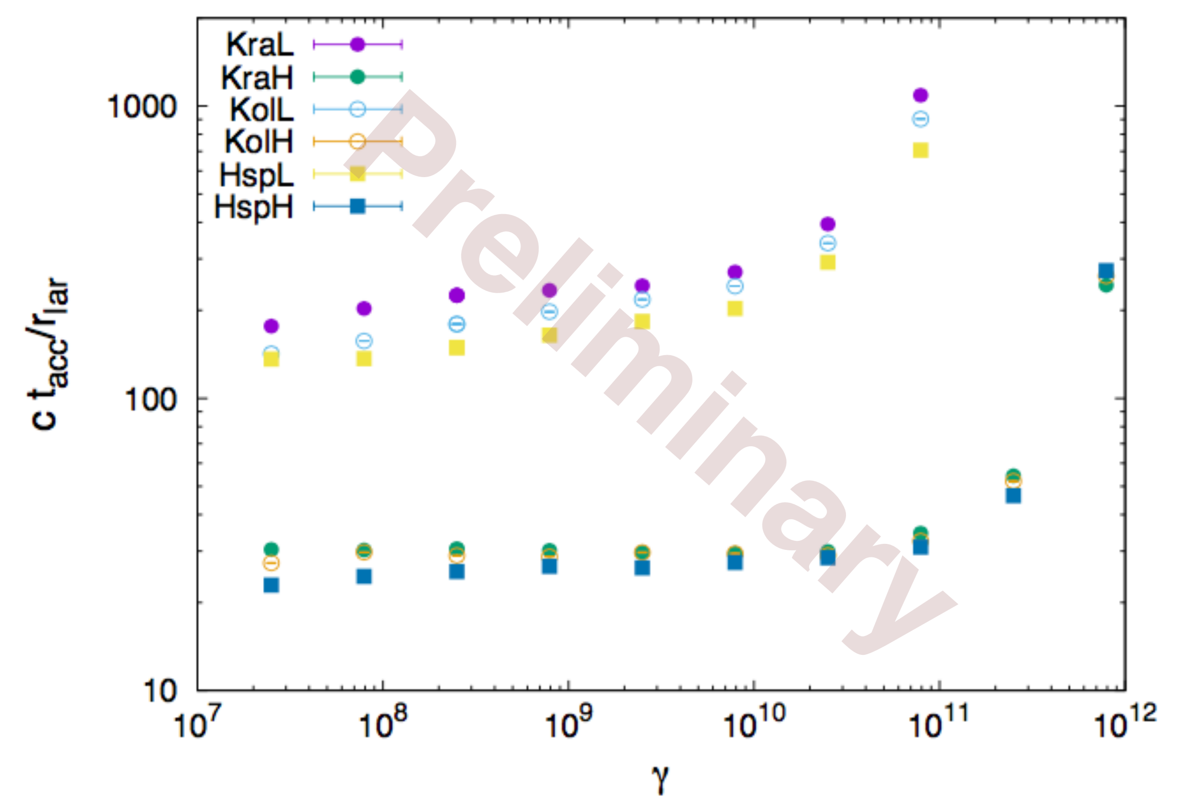


Jet has top hat velocity profile,
with uniform mean Bfield parallel to jet axis

O’Sullivan, Taylor & BR, in prep.

Shear Acceleration times

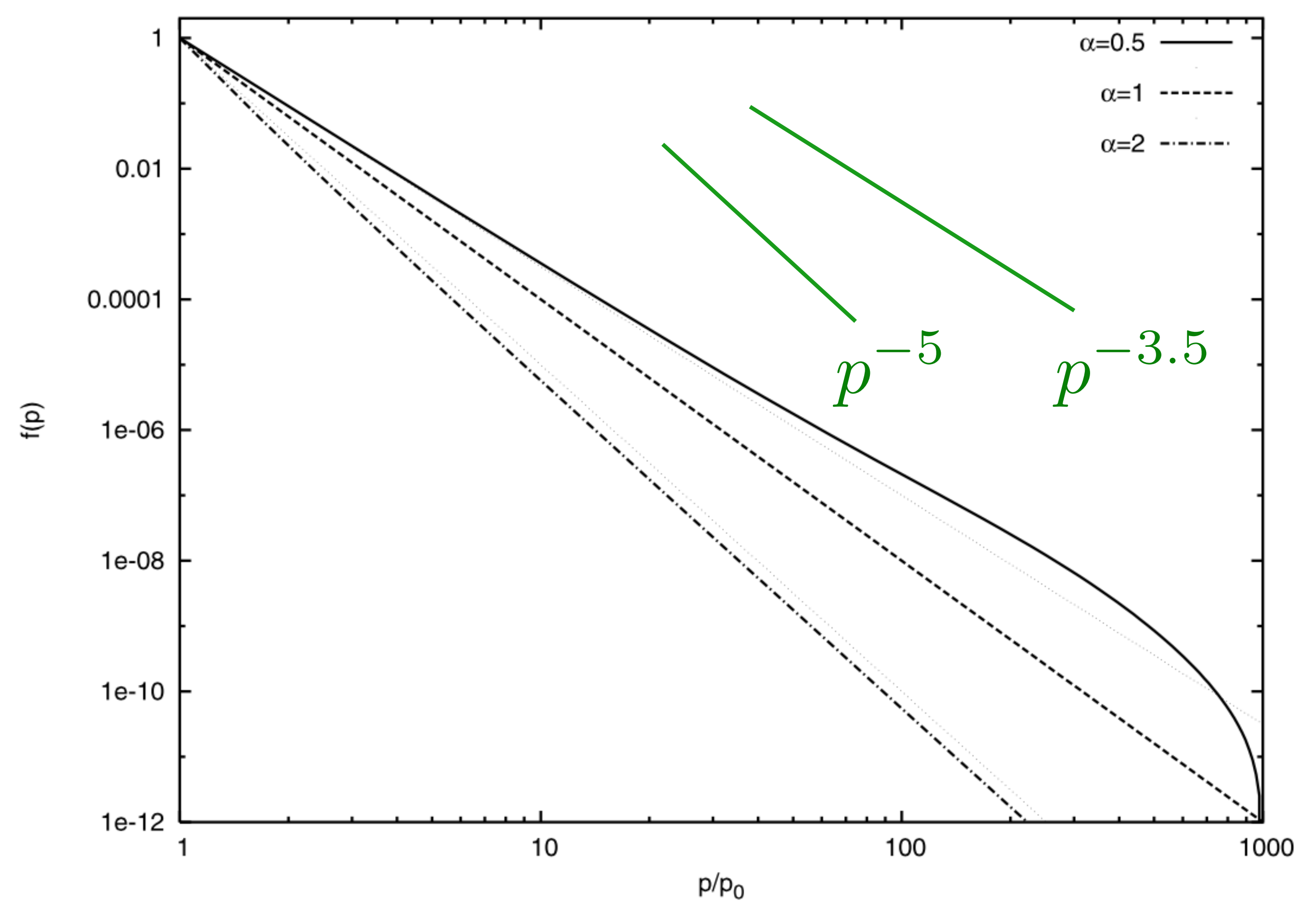
Test particle simulations in cylindrical jet



Initial results suggest acceleration rate insensitive to shape of turbulence spectrum, depending only on amplitude,
Potential source of UHECRS?

O'Sullivan, Taylor & BR, in prep.

Acceleration in gradual shear flows



Rieger & Duffy 06

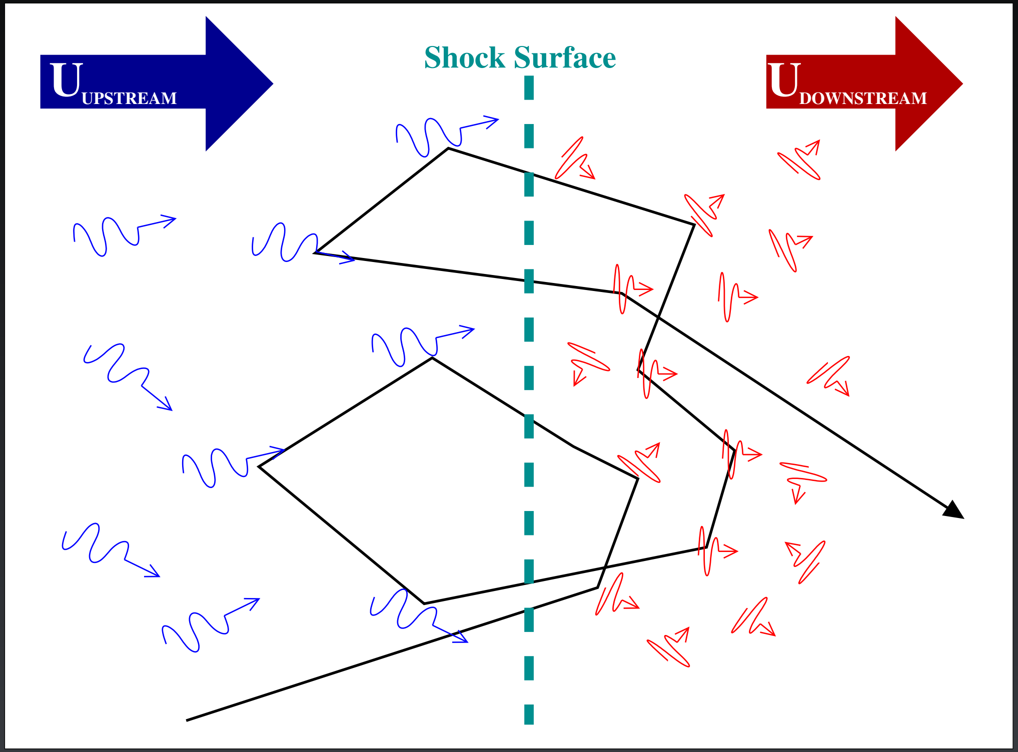
Accelerated particle distribution for different scattering rates $\tau_{\rm sc} \propto p^{\alpha}$ with synchrotron cooling

Can we generalise these results to include non-uniform u and B ?

Fermi Acceleration at Shocks

Fermi Acceleration at Non-Relativistic Shocks

Krymskii 77, Axford et al. 77, Bell 78, Blandford & Ostriker 78



Situation is partly simplified at shocks, as acceleration and escape are now intimately linked.

Assumes particles are efficiently isotropised in the local fluid frame

$$\lambda_{\text{MFP}} \equiv \frac{v}{\nu_{\text{sc}}} \ll \frac{N}{|dN/dx|}$$

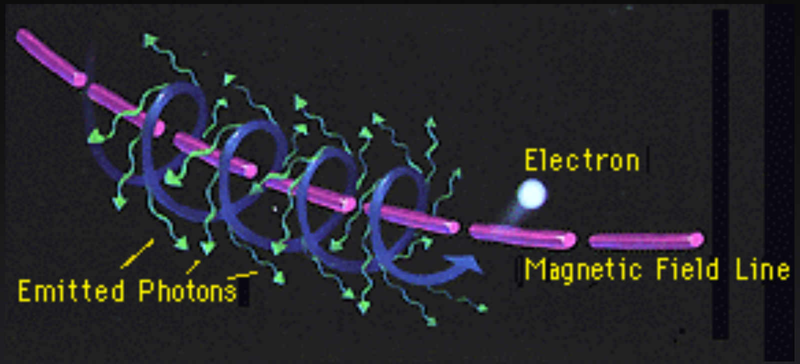
No inherent momentum scale in the system , naturally produces power-laws which depend only on single parameter: $r = u_{\text{us}}/u_{\text{ds}}$

$$\frac{dN}{dE} \propto E^{-(r+2)/(r-1)} = E^{-2}$$

(for strong shocks $r \approx 4$)

Power-law spectra and Radiative Signatures

Synchrotron spectra reveal electron spectral shape



- Electron power-law distribution

$$dN \propto E^{-s} dE = \gamma^{-s} d\gamma$$

- Larmor's formula

$$dU \propto \gamma^2 dN$$

- Peak Synchrotron frequency

$$\omega_{\rm syn} \approx 0.5\gamma^3 \omega_{\rm g} \propto \gamma^2$$

- Simple change of variable

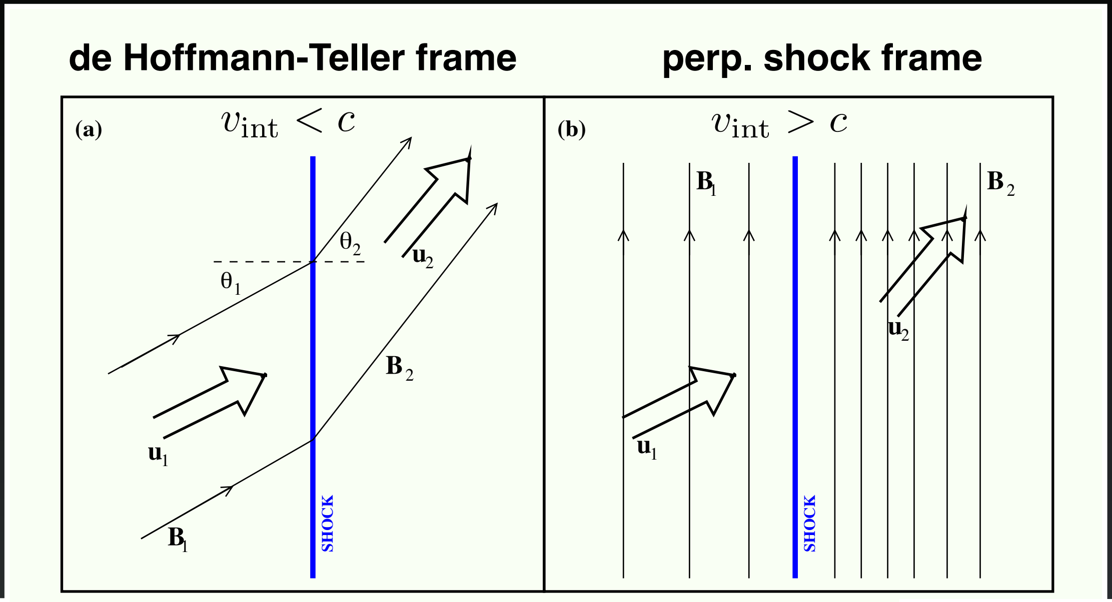
$$\frac{dU}{d\omega} \propto \omega^{-(s-1)/2} = \omega^{-0.5}$$

(for s = 2)

Wonderful news if we only ever observed $\omega^{-0.5}$ spectra !!

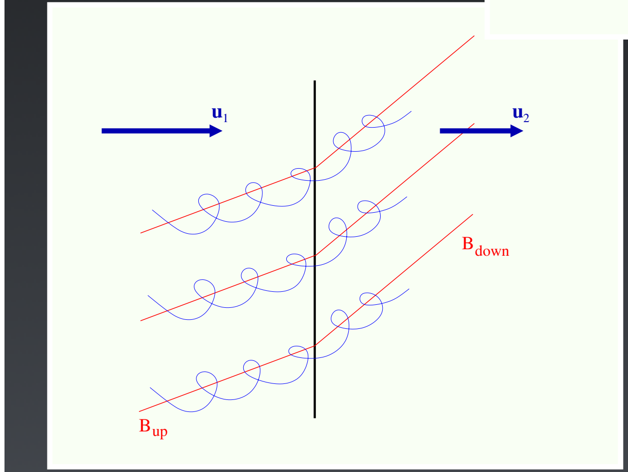
How can we produce different spectra?

Obliquity effects

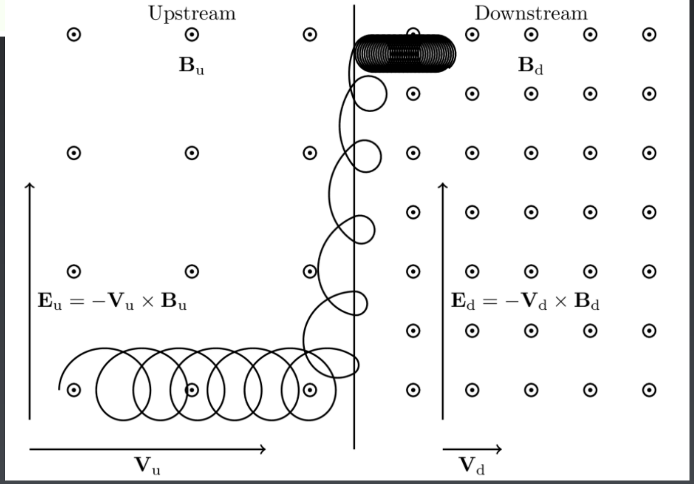


de Hoffmann-Teller frame **perp. shock frame**

$$v_{\rm int} = v_{\rm sh}/\cos\left(\theta_{\boldsymbol{B}\cdot\boldsymbol{n}}\right)$$

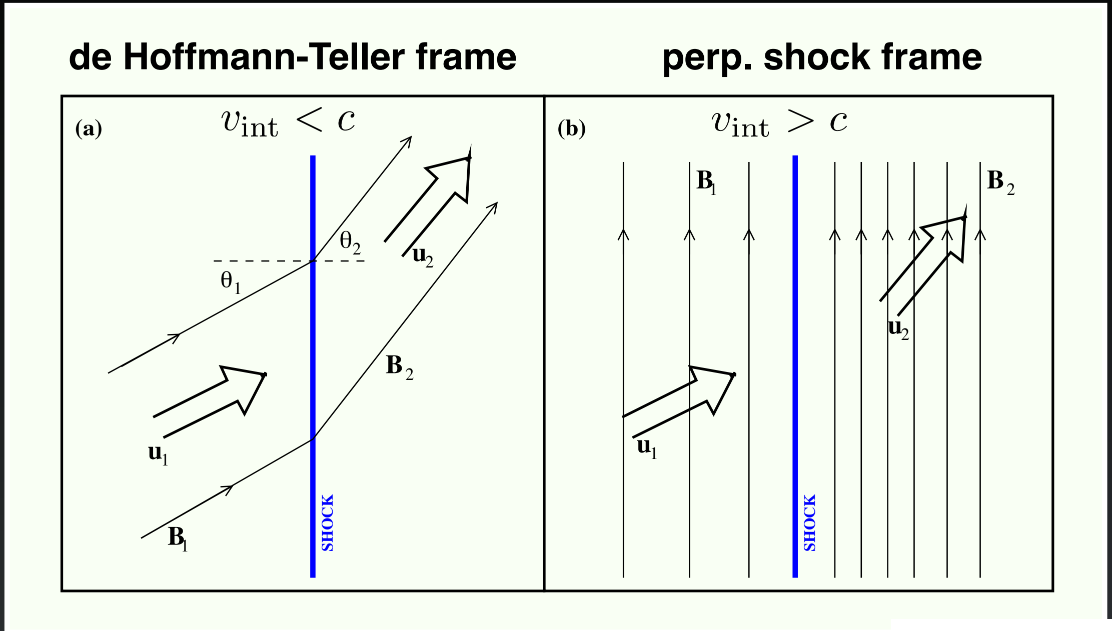


No Scattering

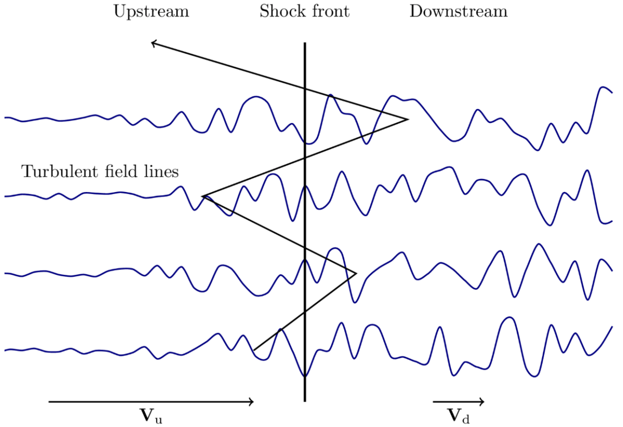


credit: M. Pulupa’s website

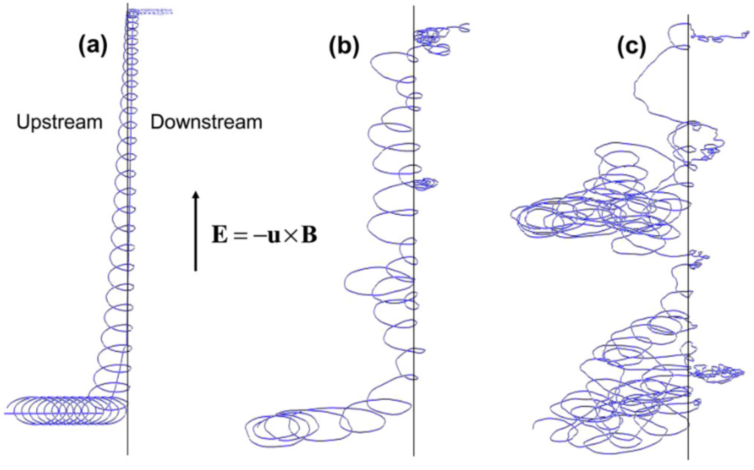
Obliquity effects



$$v_{\rm int} = v_{\rm sh}/\cos\left(\theta_{\boldsymbol{B}\cdot\boldsymbol{n}}\right)$$



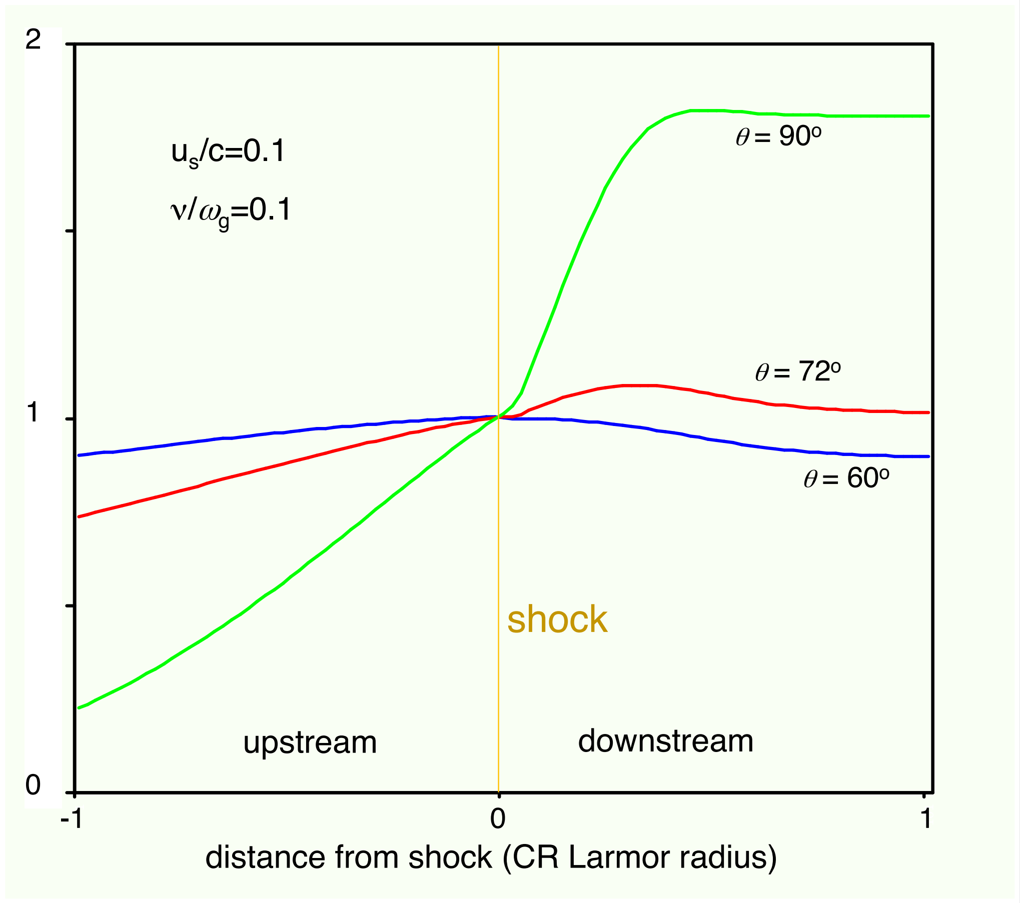
Scattering



Oblique shocks “faster” accelerators, although for finite systems, maximum energies comparable

Obliquity effects

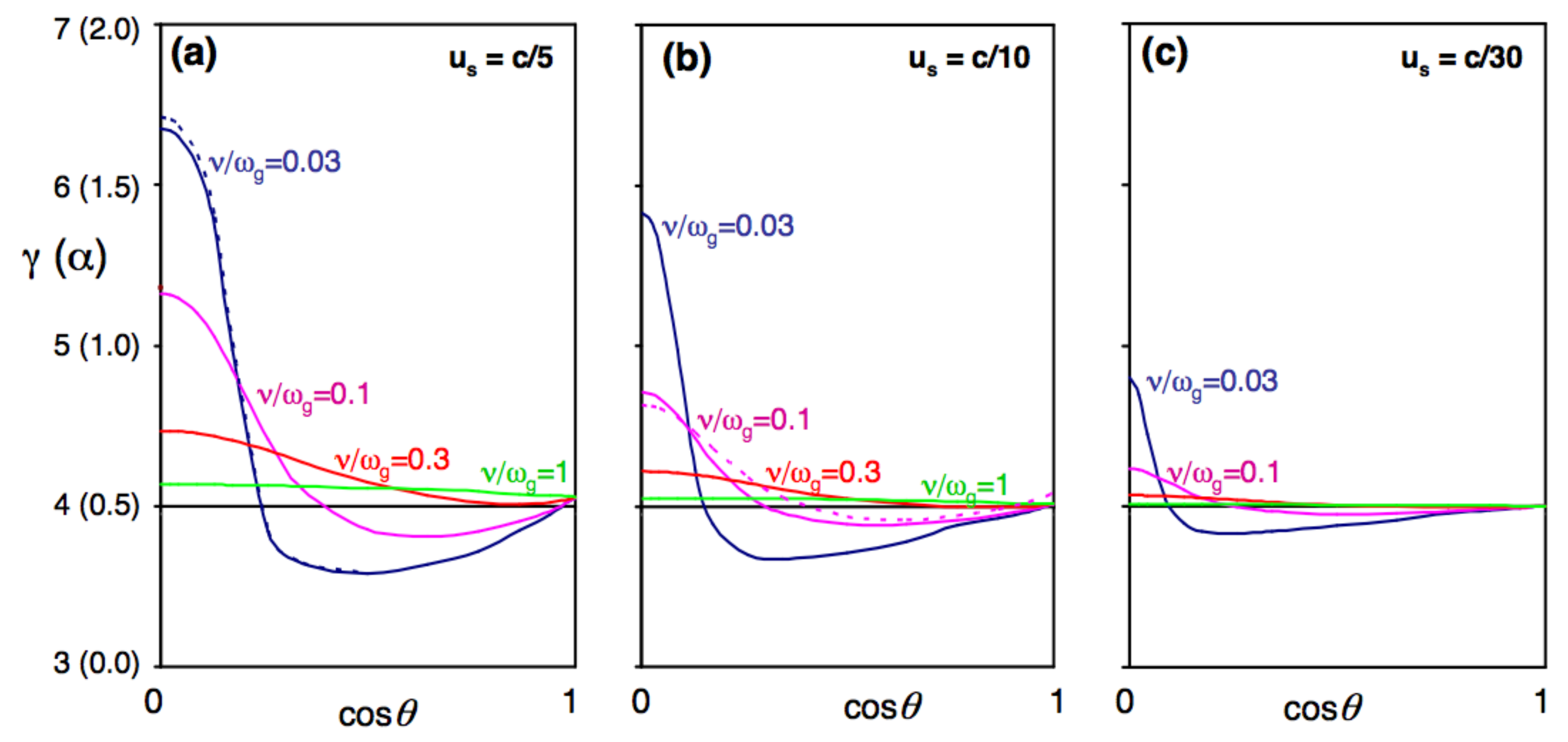
Test particle Fokker-Planck simulations (Bell, Schure, BR, 11)



Abrupt change in field direction results in $\lambda_{\rm MFP} \equiv \frac{v}{\nu_{\rm sc}} \ll \frac{N}{|dN/dx|}$ condition breaking down at shock

Mean field effects

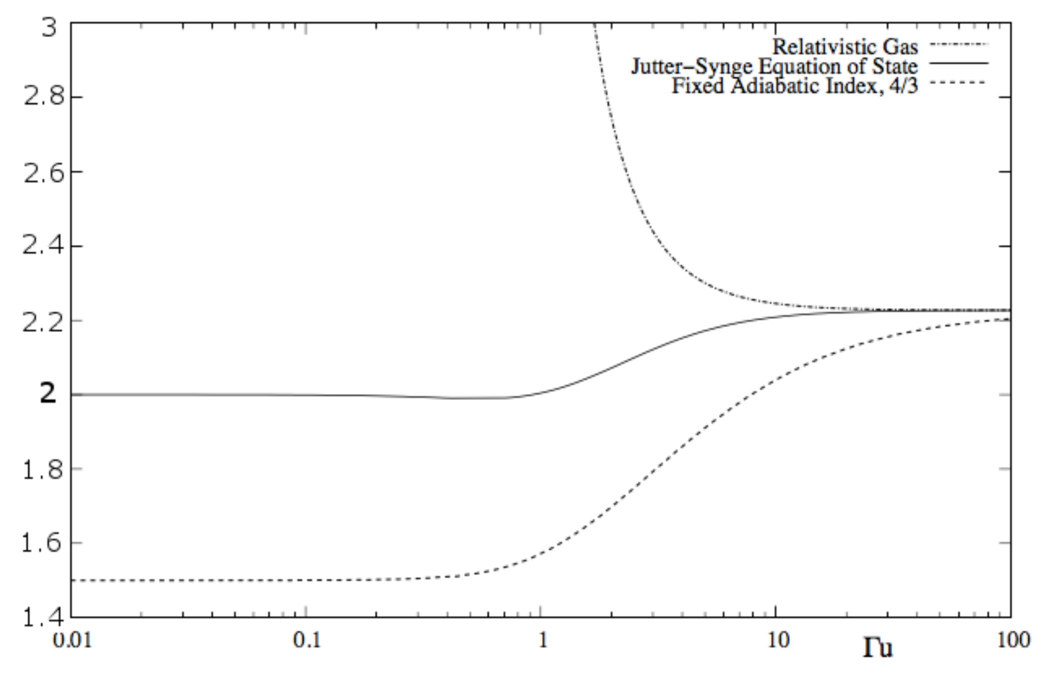
$\gamma = s + 2$



Note: Unless $\nu \approx \omega_g$, radio spectrum is particularly sensitive to magnetic obliquity at high velocities

Non-relativistic to Relativistic

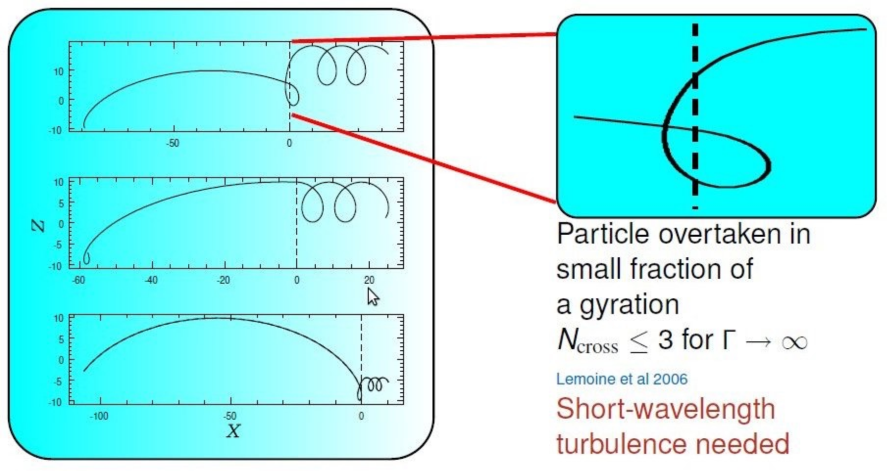
Isotropic pitch angle diffusion model (QJ method)
e.g. Kirk et al 2000



From P. Dempsey's Thesis 2007

Asymptotic power-law 2.22

$$\frac{dU}{d\omega} \propto \omega^{-0.61}$$



Particle overtaken in small fraction of a gyration

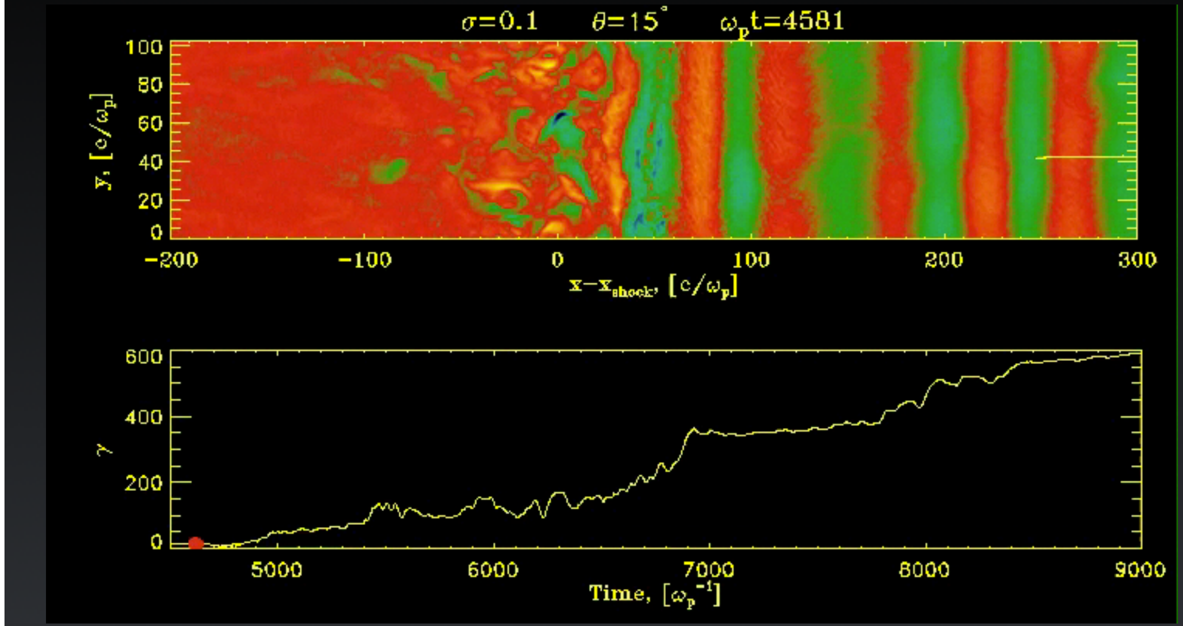
$N_{\rm cross} \leq 3$ for $\Gamma \rightarrow \infty$

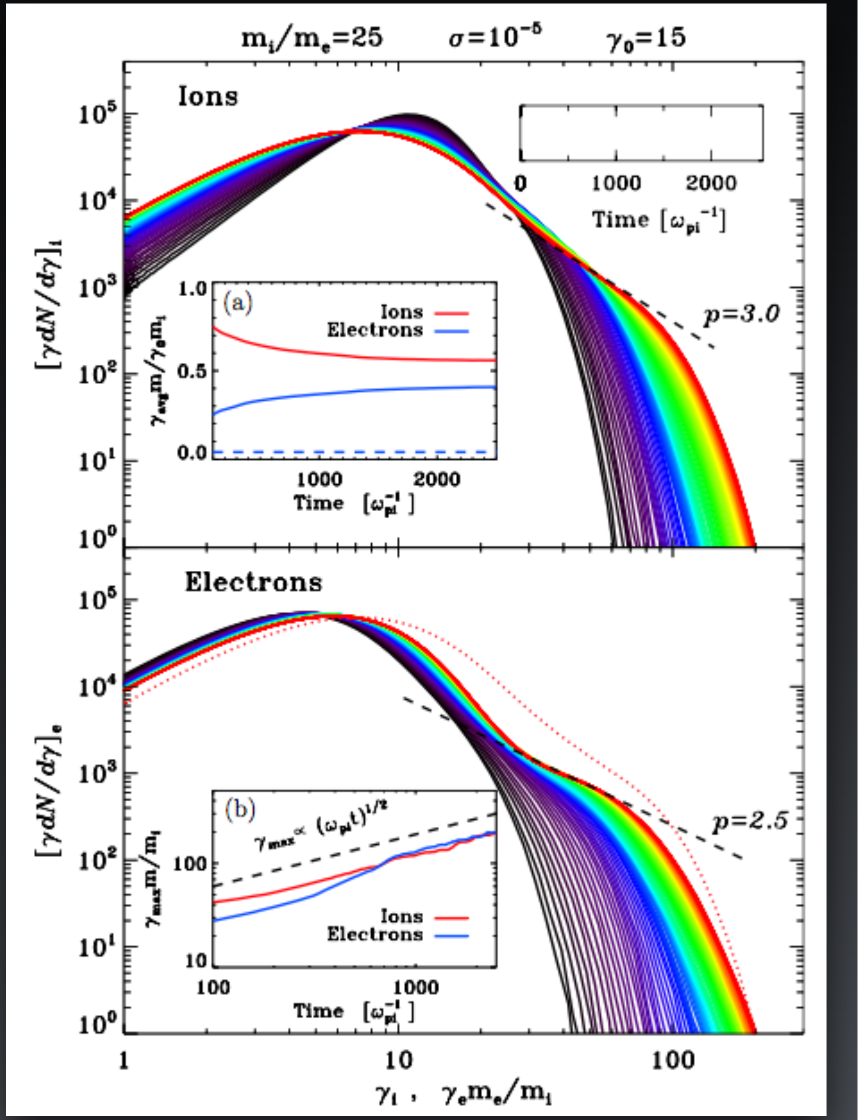
Lemoine et al 2006

Short-wavelength turbulence needed

Note: collision induced drifts not captured in this model, hence no discussion of obliquity (although probably not terribly important for $\Gamma \gg 1$)

Particle in Cell simulations





Sironi et al 13

PIC simulations provide “self-consistent” approach to relativistic shock physics

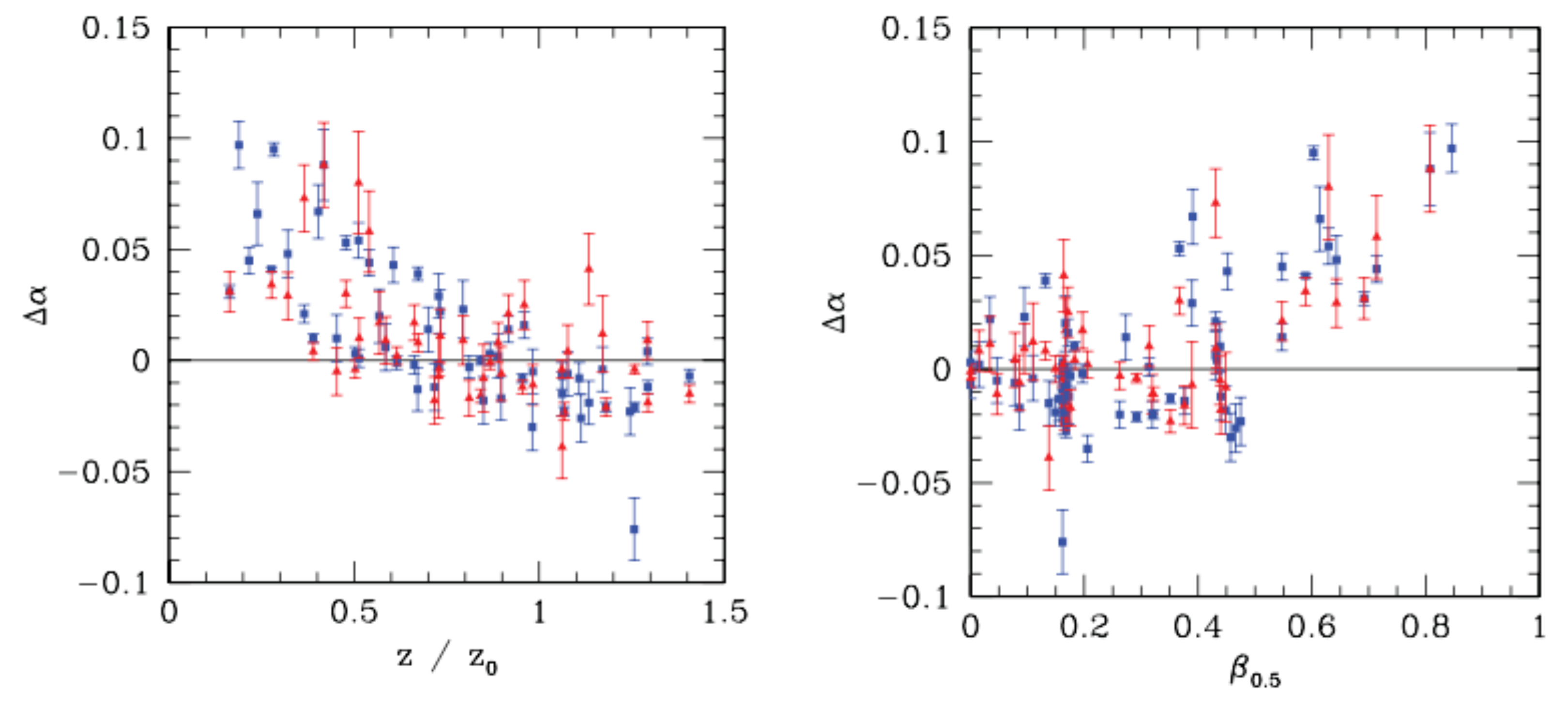
Shock acceleration occurs if shock is:

- weakly magnetised $(\sigma < 10^{-3})$
- or sub-luminal $(\theta_{B\cdot n} < \Gamma^{-1})$

Supports pitch angle scattering picture of acceleration at relativistic shocks

Implications for FR I sources

Observations of FR I sources



Laing & Bridle 13

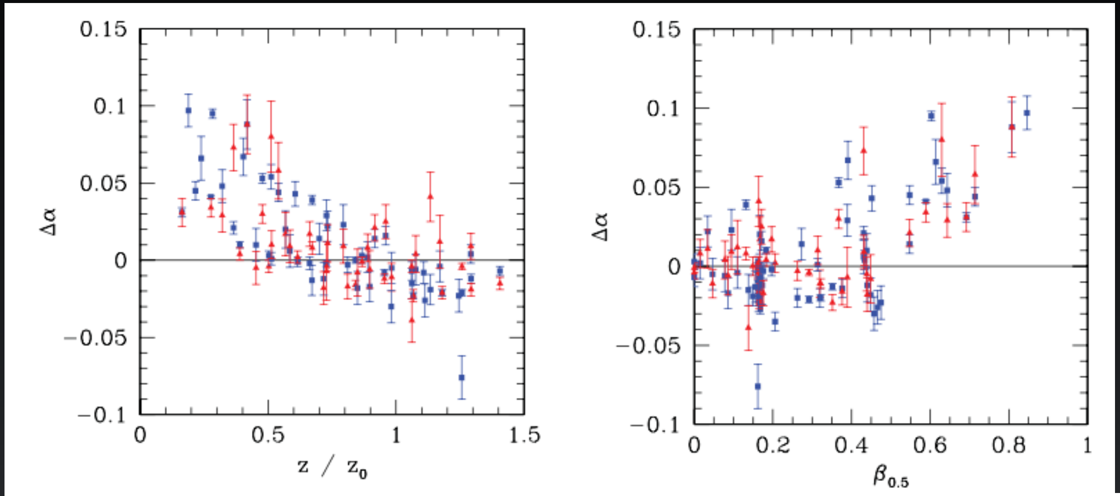
Mean spectral index $\langle \alpha \rangle \sim 0.6$

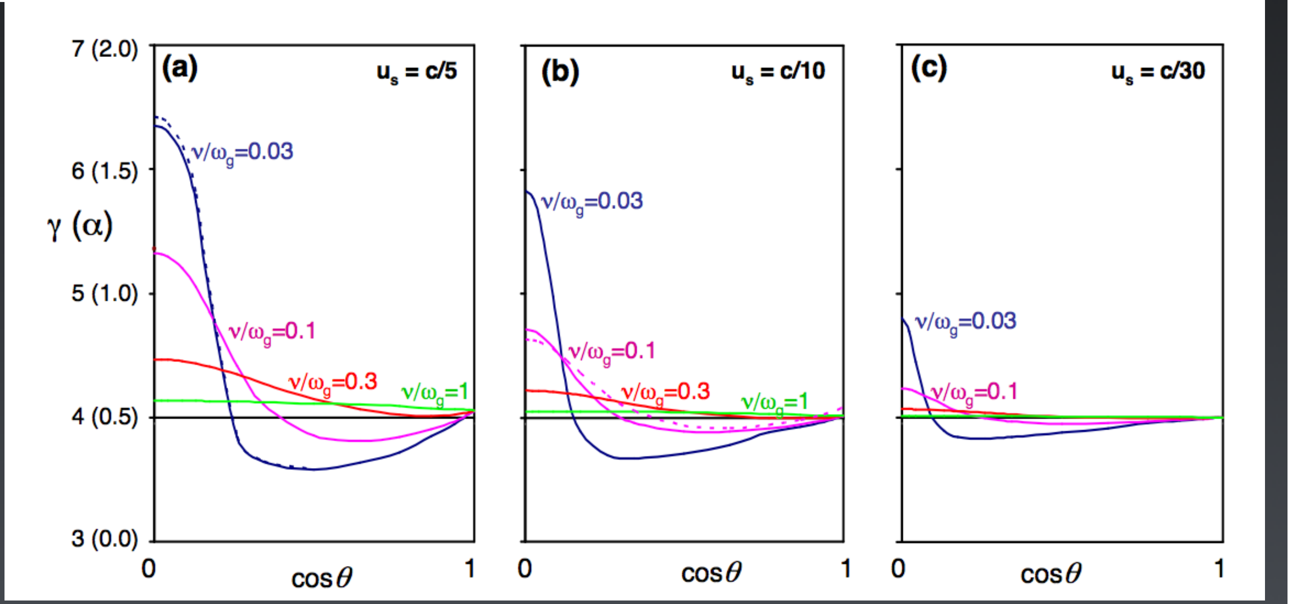
Spectral flattening with distance from core.

Difficult to reconcile with synchrotron cooling picture

Implied electron power-law spectra flattening from s = 2.32 - 2.18

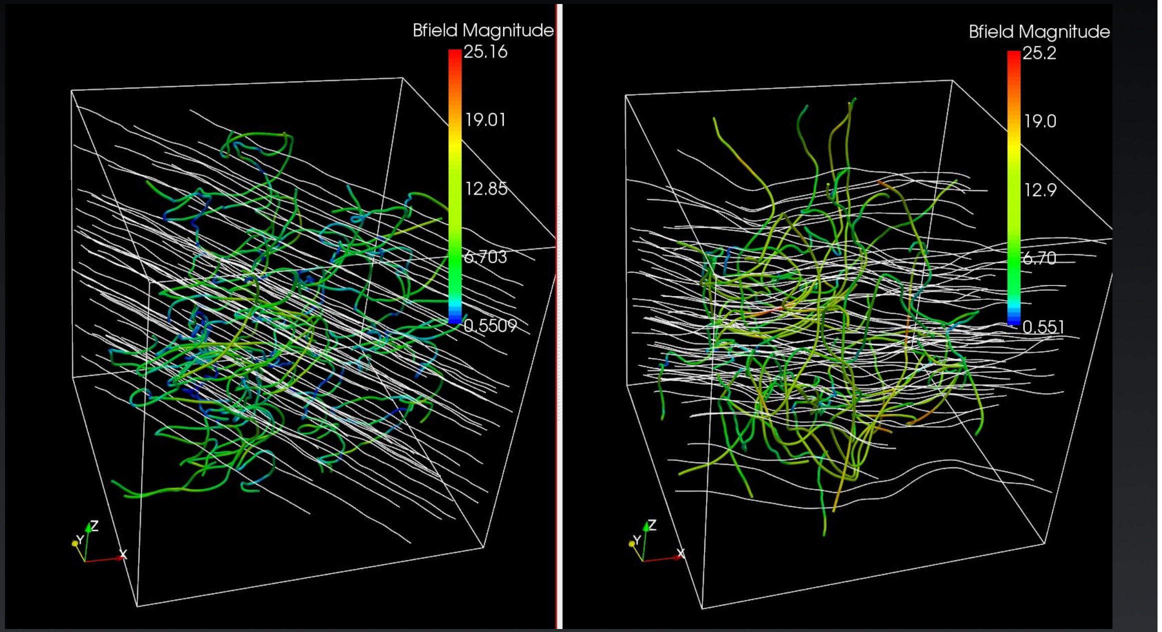
Can shocks account for spectra in FR I jets?





Consistent with shock acceleration picture, provided $\nu/\omega_{\rm g} \sim 1$

Implications of universal Bohm scattering



BR & Bell 13

Uniformity of radio brightness implies shocks (if present) are distributed along jet, with random orientations .

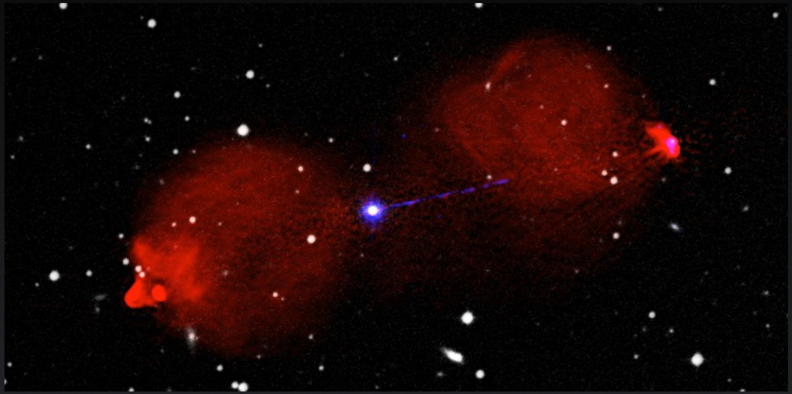
IF shocks are the source of radio emitting electrons, the scattering must be very efficient to avoid a large spread in $\Delta\alpha$

Self-generation of Bohm like scattering fields have been found, (numerically) in supernova relevant studies, but require efficient cosmic-ray acceleration (to generate the necessary currents).

Typical energy hierarchy: $\rho u_{\rm sh}^2 > U_{\rm cr} > U_{\rm th} > U_B$

Radio Hot-spots

Cut-off spectra and Scattering Rates

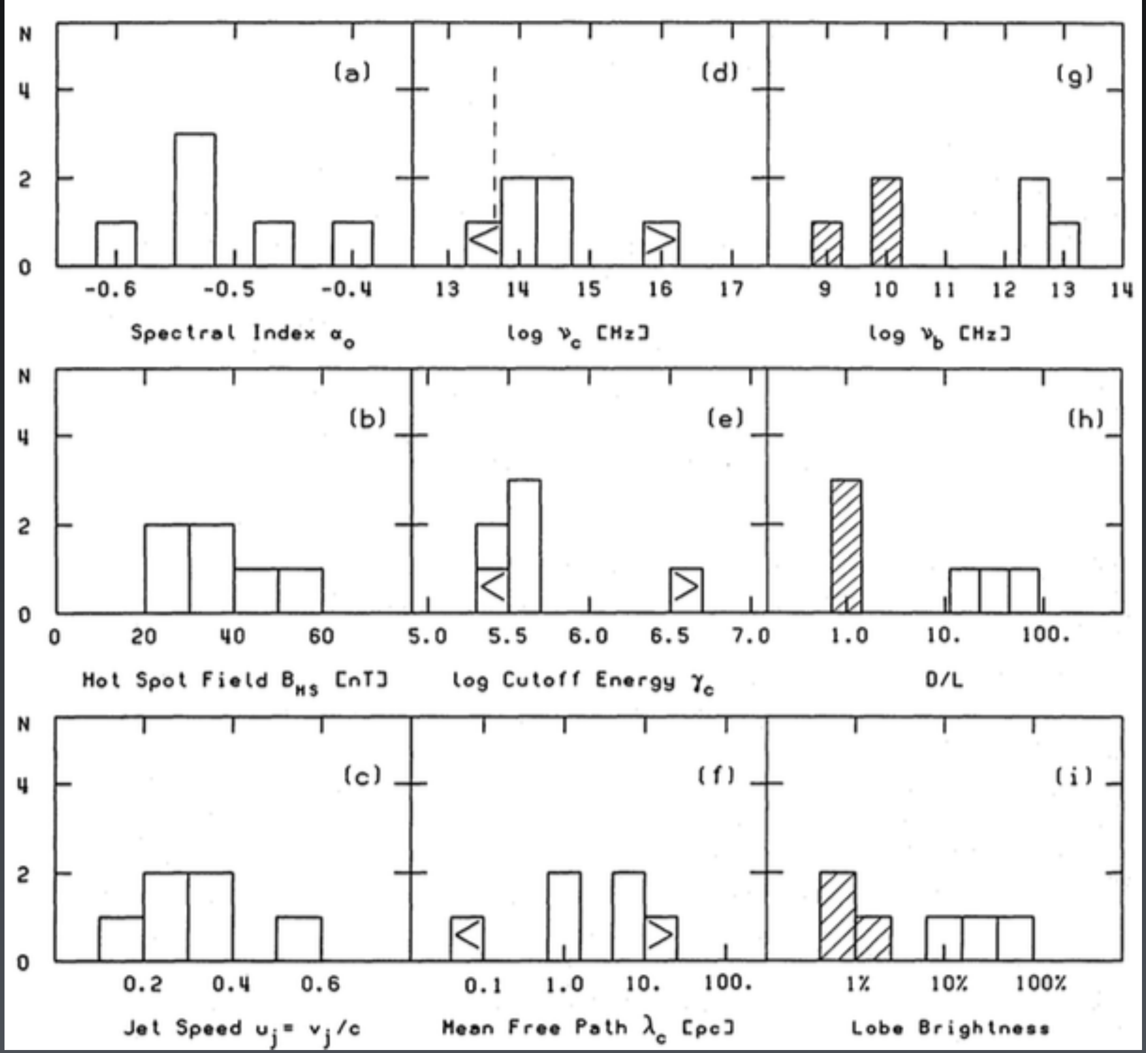


Pictor A, credit: Emil Lenc

Radio hotspots typically show very different behaviour:

- spectral indices ~0.5 +-
- Scattering nowhere near Bohm

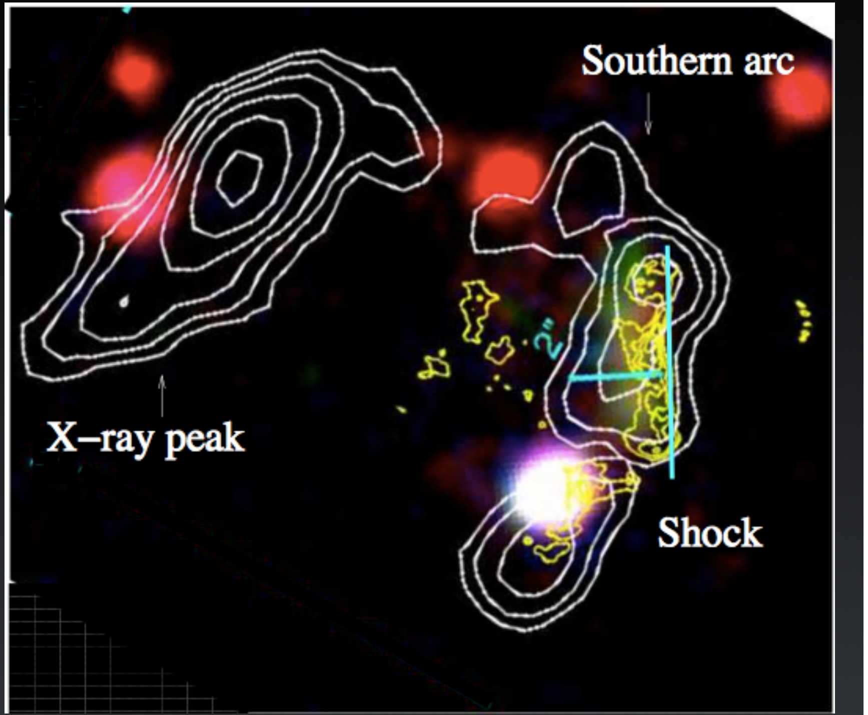
$$\frac{\nu}{\omega_g} \approx 10^{-3}$$



Meisenheimer et al 89

Scattering rates and shock physics

4C74.26 recently revisited by Araudo et al '15

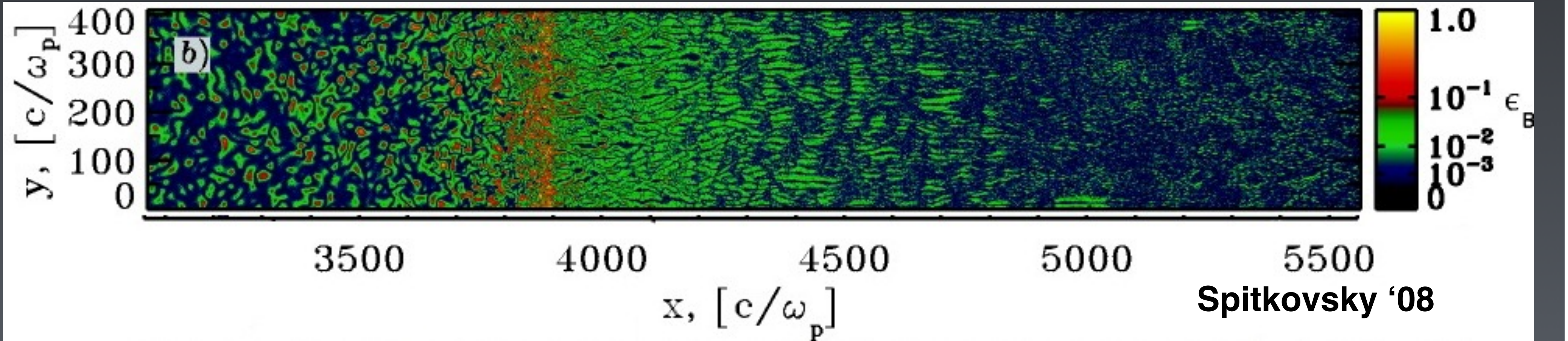


Cooling morphology suggests inefficient acceleration $\frac{\nu_{\rm sc}}{\omega_g} \approx 10^{-6}$

With some uncertainty, this corresponds to small angle scattering in cells of size s

$\frac{\nu_{\rm sc}}{\omega_g} \approx \frac{s}{r_g}$ where $s \sim 0.01(c/\omega_p)$

Consistent with Weibel picture of fast shocks?



Spitkovsky '08

Summary

Fermi acceleration offers a simple framework for investigating non-thermal radiation spectra in astrophysical sources

Many competing mechanisms, but acceleration timescales reasonably well understood
Can be readily accommodated in phenomenological models

Second order Fermi processes may contribute to emission in fast jets / radio lobes

In the context of FR I sources, IF distributed shock acceleration is occurring, suggests efficient proton acceleration

Radio hot spots in FR II sources appear consistent with Weibel mediated picture of fast shocks